WroNG – Wrocław Neutrino Generator of events for single pion production

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We constructed a new Monte Carlo generator of events for neutrino CC single pion production on free nucleon targets. The code uses dynamical models of the DIS with the PDFs modified according to the recent JLab data and of the Δ excitation. A comparison with experimental data was done in three channels for the total cross sections and for the distributions of events in invariant hadronic mass.

1. INTRODUCTION

Neutrino-nucleon (or nucleus) CC interactions are described in a framework of three different theoretical schemes: quasi-elastic, resonance, and deeply inelastic (DIS). It is a nontrivial task to put them together in a Monte Carlo generator of events. Most problems arise in the resonance region. There are several models of single pion production (SPP) due to resonance production but some non-resonant background is also required. Then it is necessary to join such a model with the DIS part which must be extrapolated far away from the kinematical region in which it is reliable. In existing MC codes [1] the Rein-Sehgal model [2] is most often used to describe the dynamics of SPP. It includes contributions from several resonances of the mass up to 1.8 GeV added in the coherent way. The non-resonant background is then added incoherently in order to fit the experimental data. An important improvements to existing MC codes can come from precise JLab experimental data from electron scattering experiments [3]. It is known how to construct good experimental fits for the structure functions F_1 and F_2 which in the resonance kinematical region average over resonance peaks [4]. In the neutrino-nucleon cross section the axial structure function F_3 is also present whose modification cannot be deduced from electron experiments. As a first guess one can assume that the modification is analogous to that applied to the $F_{1,2}$ and investigate consequences of such assumption.

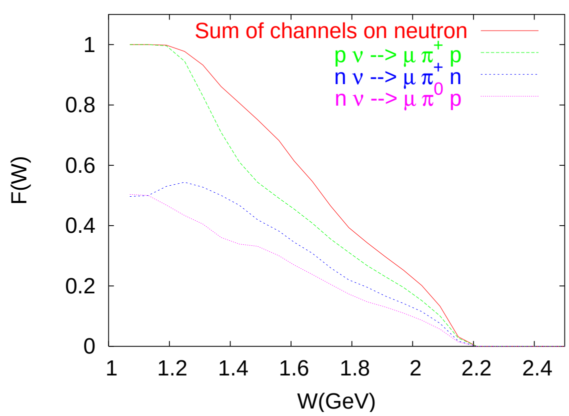

Figure 1. Fraction of single pion production contribution in overall Deep Inelastic Scattering cross section

This was the starting point for our investigation. We shall describe a construction of MC code WroNG (WROcław Neutrino Generator) for SPP which incorporates explicit Δ excitation model and three exclusive SPP channels extracted from the DIS formalism. We focused on SPP channels since inclusion of the remaining dynamics (quasi-elastic channel and more in-

*The authors were supported by KBN grant 105/E-344/SPB/ICARUS/P-03/DZ211/2003-2005

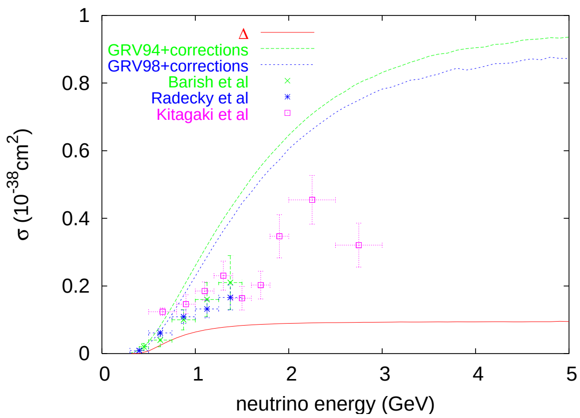

Figure 2. Total cross section in the channel $\nu_\mu n \to \mu^- \pi^+ n$

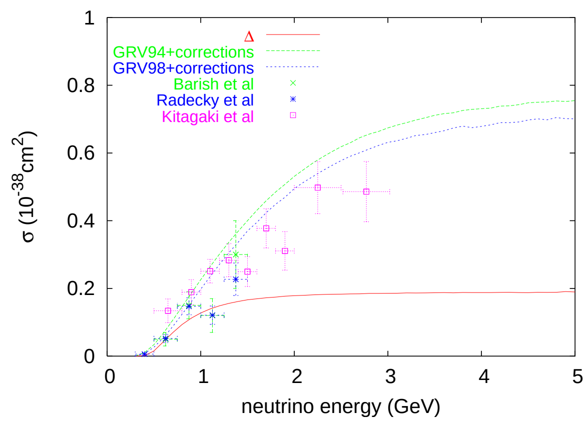

Figure 3. Total cross section in the channel $\nu_\mu n \to \mu^- \pi^0 p$

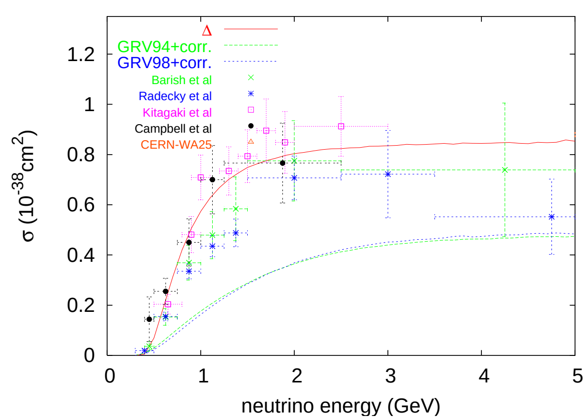

Figure 4. Total cross section in the channel $\nu_\mu p \to \mu^- \pi^+ p$

elastic reactions described by DIS formalism) is straightforward. Our code can supplement the NUX+FLUKA scheme which does not contain a resonance contribution [5].

In order to evaluate SPP in the framework of the DIS formalism we introduced three functions (one for each channel) of kinematical variables. The functions measure the probability that after fragmentation and hadronisation the final hadronic state is that of SPP. We obtained these functions from the NUX+FLUKA simulations which are based on the LUND algorithm [6]. They turned out to be monotonously decreasing functions of the hadronic mass W, taking values in a range from 1 to 0 (see fig. 1).

The functions we introduced above have been used to define the differential cross section for SPP in the DIS formalism (there are three identical definitions for each reaction channel):

$$\frac{d^2\sigma^{DIS-SPP}}{dW\,d\omega} = \frac{d^2\sigma^{DIS}}{dW\,d\omega} \cdot F(W) \tag{1}$$

where σ^{DIS} is the DIS inclusive cross section. W and ω denote hadronic mass and energy transfer respectively.

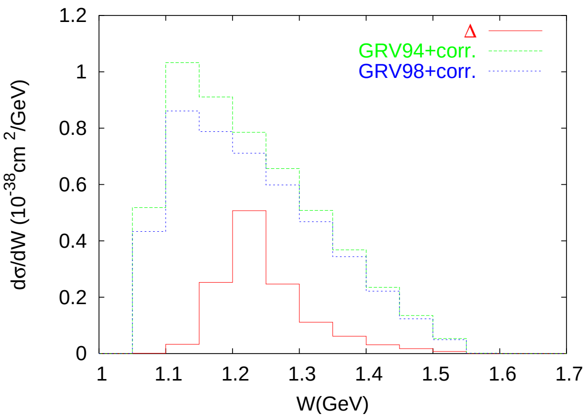

Figure 5. Hadronic mass distribution in the channel $\nu_\mu n \rightarrow \mu^- \pi^+ n$ at $E_\nu = 1GeV$

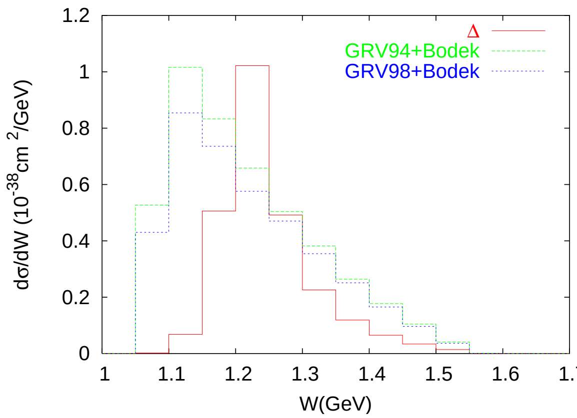

Figure 6. Hadronic mass distribution in the channel $\nu_\mu n \rightarrow \mu^- \pi^0 p$ at $E_\nu = 1GeV$

In our work we had to solve two problems. The first was to join Δ and DIS contributions. The second problem was to add appropriate non-resonant contributions. In what follows by DIS we mean exclusive SPP channels contained in inclusive DIS. We joined two dynamical mechanisms in the cross section expression according to the values of the hadronic invariant mass in the kinematically allowed region. The basic idea was that for small (i.e. from the threshold $W = M + m_\pi$ to about $1.4\,GeV$) values of W the dynamics is that of Δ excitation while for larger W the dynamics is that of DIS. In order to make the transition smooth we fixed a region from W_1 to W_2 in which the probability to choose either of two dynamics changed linearly in the MC way.

We mimic the "non-resonant" background in the region of small values of W by an admixture of the DIS contribution. It was done in the MC way and amount of the DIS contribution was described by a parameter α a value of which was fixed by making a comparison with experimental data separately in each exclusive channel. To summarize the formula for the cross section in each reaction channel can be written as:

$$
\begin{aligned}
&\frac{d^2\sigma}{dW d\omega} = \theta\left(W_1 - W\right) \\
&\quad\left(\alpha \frac{d^2\sigma^{DIS-SPP}}{dW d\omega} + (1-\alpha)\,\frac{d^2\sigma^{\Delta}}{dW d\omega}\right) \\
&+\theta\left(W - W_1\right)\theta\left(W_2 - W\right) \\
&\quad\left(\left(\alpha + (1-\alpha)\,\frac{W - W_1}{W_2 - W_1}\right)\frac{d^2\sigma^{DIS-SPP}}{dW d\omega}\right. \\
&\qquad\left. + (1-\alpha)\,\frac{W_2 - W}{W_2 - W_1}\frac{d^2\sigma^{\Delta}}{dW d\omega}\right) \\
&+\theta\left(W - W_2\right)\frac{d^2\sigma^{DIS-SPP}}{dW d\omega}
\end{aligned}
\qquad (2)
$$

2. RESULTS

First we present basic ingredients of our construction: the Δ excitation model (taken from the Marteau model [7]) and the model of SPP based on DIS. We show the total cross sections in three reaction channels (fig. 2-4) with experimental points taken from papers: [8], [9]. We also show distributions of events in the hadronic

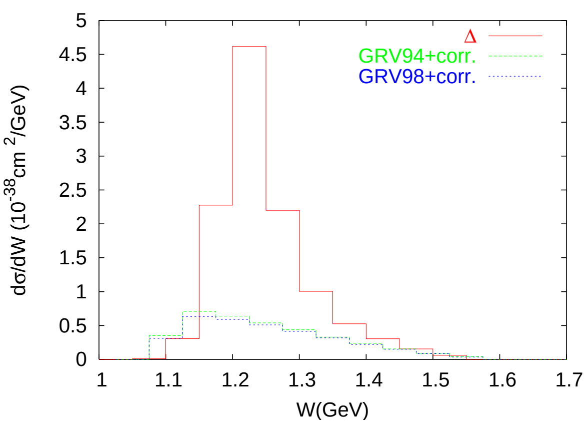

Figure 7. Hadronic mass distribution in the channel $\nu_\mu p \to \mu^- \pi^+ p$ at $E_\nu = 1 GeV$

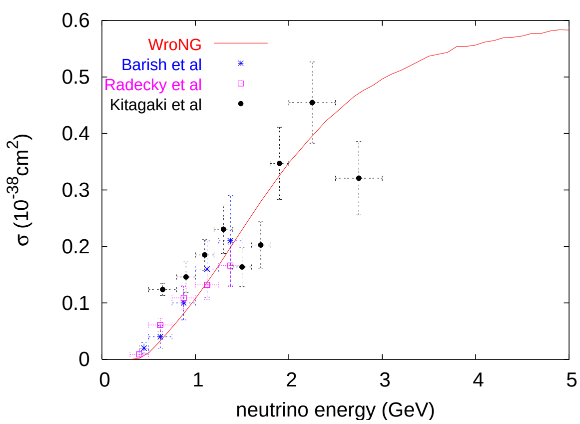

Figure 8. WroNG predictions in the channel $\nu_\mu n \to \mu^- \pi^+ n$ and experimental data (total cross section) from [8] [9]

mass for neutrinos of energy 1 GeV (fig. 5-7). In the DIS part we did computations for two sets of PDF: modifications of GRV94 and GRV98. Differences between them are very small and in what follows we restrict ourselves to GRV98 with corrections.

In the channel $\nu_\mu n \to \mu^- \pi^+ n$ the DIS cross section is much bigger than for the Δ excitation one (see fig. 2). If compared with experimental data we see that the DIS predictions are above experimentally observed while those of the Δ model below. In fig. 5 the DIS differential cross section of hadronic mass is bigger than of the Δ in the whole kinematical domain.

In the channel $\nu_\mu n \to \mu^- \pi^0 p$ the situation is quite different (see fig. 3). At smaller values of the neutrino energy E (about 1 GeV) both models predict similar values of the total cross section close to experimentally measured. For higher values of neutrino energy the DIS predictions agree with the experimental data while the Δ excitation model predictions are too low. In fig. 6 differential cross sections reveal that while the cross sections are similar in the total area below the curves, the shapes of the hadronic mass distributions of events are very different. In this channel we see a nice manifestation of the quark-hadron duality: the DIS contribution average over resonance peak.

In the channel $\nu_\mu p \to \mu^- \pi^+ p$ the Δ excitation model predicts much higher values of the cross section which are also close to the experimentally measured (see fig. 4, 7).

We conclude that each channel has its unique features and has to be treated independently. We also note that quark-hadron duality is seen in only one SPP channel. It suggests that modifications of PDF we applied in our computations are not yet good enough.

Many choices for W_1, W_2 for each channel separately were checked in order to find the most suitable one. The results did not depend much on the choice and we fixed for all three channels: $W_1 = 1.3\ GeV$ and $W_2 = 1.6\ GeV$.

Total cross sections depend in a substantial way on α. In the channel $\nu_\mu p \to \mu^- \pi^+ p$ an increase of α makes the cross section smaller, in other two channels the dependence is opposite. We also looked at distributions of events in the hadronic mass. We compared our MC results with Kitagaki et al. data [9] because they have the best

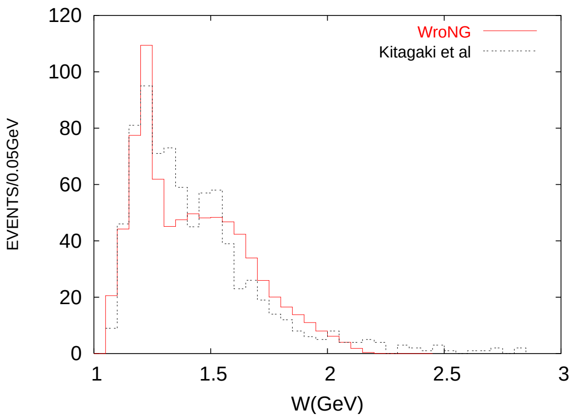

Figure 9. WroNG predictions in the channel$\nu_\mu n \rightarrow \mu^-\pi^+ n$ and experimental data (hadronic mass distribution) from [9]

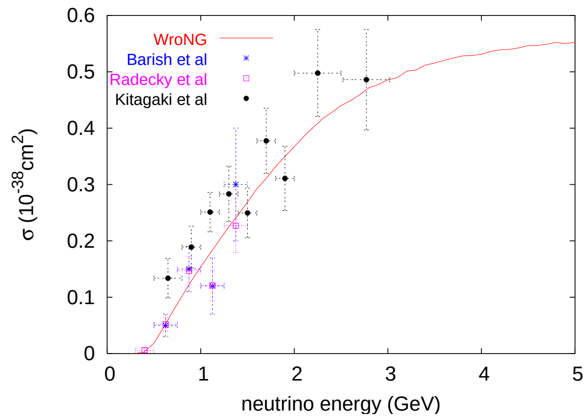

Figure 10. WroNG predictions in the channel $\nu_\mu n \rightarrow \mu^-\pi^0 p$ and experimental data (total cross section) from [8] [9]

statistics. We took into account experimentally reconstructed spectra of neutrinos and we produced samples of events with the same spectrum. The number of events has been chosen to be the same as in the oryginal experiment so that this part of the analysis applied only to the shapes of hadronic mass distributions of events.

In two channels on the neutron the value of α determines the height of the Δ resonance peak. The transition region (W_1, W_2) can manifest itself as a resonance-like peak at values of W close to W_2. It is only by chance that such higher resonance peak can be seen in the experimental data. With an increase of α the resonance peak becomes lower but at the expense of too many events at lower values of hadronic mass and in clear contradiction with experimental data. The best value of α is a compromise between two described tendencies.

In figs. 8-13 we show a comparison of our best qualitative fits with Kitagaki et al. experimental data in three reaction channels. We took $\alpha = 0.2$ for $\nu_\mu n \rightarrow \mu^-\pi^+ n$ channel, $\alpha = 0.3$ for $\nu_\mu n \rightarrow \mu^-\pi^0 p$ channel and $\alpha = 0$ for $\nu_\mu p \rightarrow \mu^-\pi^+ p$ channel. Taking into account the simplicity of our construction we find the agreement satisfactory.

We plan to improve WroNG in the following way:

- a non-resonant background will be introduced in theoretically justified way using Fogli-Nardulli [10] or Lee-Sato [11] results
- three functions $F_{SPP}(W)$ will be derived directly from PYTHIA/JETSET or LEPTO
- the model will be extended to describe SPP on nucleus targets

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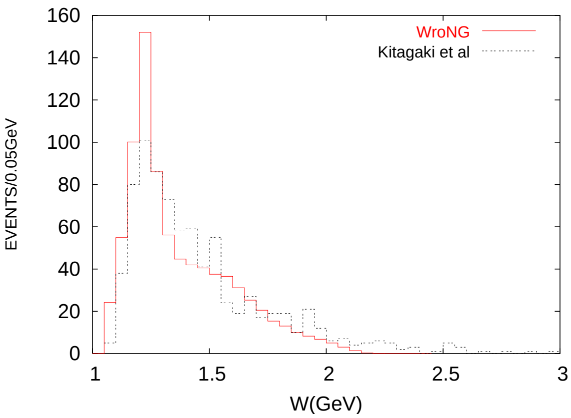

Figure 11. WroNG predictions in the channel $\nu_\mu n \to \mu^- \pi^0 p$ and experimental data (hadronic mass distribution) from [9]

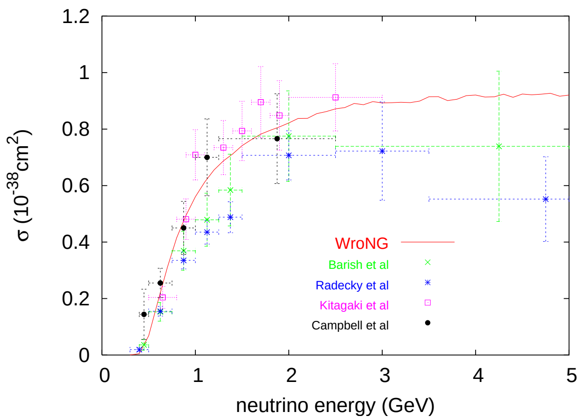

Figure 12. WroNG predictions in the channel $\nu_\mu p \to \mu^- \pi^+ p$ and experimental data (total cross section) from [8] [9]

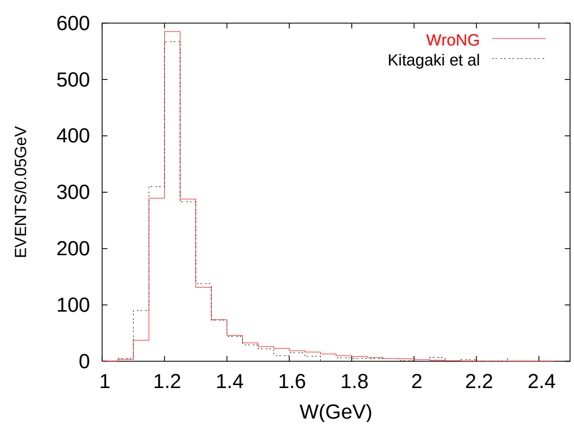

Figure 13. WroNG predictions in the channel $\nu_\mu p \to \mu^- \pi^+ p$ and experimental data (hadronic mass distribution) from [9]

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